Exploitation of Material Property Potentials to Reduce Rare Raw Material Waste

A Product State Based Concept for Manufacturing Process Improvement

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***Abstract*- Manufacturing companies today face fierce global competition and volatile and rising prices on an ever more restricted natural raw material supply market. Customers demand high quality of the purchased products and supplying companies have to find ways to fulfill these customer requirements. In general, there are two ways how companies can meet specific requirements when material properties are in the focus. On the one hand, they can choose a material which exceeds the required specifications and produce the product from that material. That way, the final product is mostly over engineered, not by over dimensioning but by the high grade material of choice. Another way is, to take a material, which basic material properties are not meeting the requirements yet and change the material properties through processing to exploit the material property potential.**

The first option can make sense when the material is widely available and reasonably priced. But most of the time, such a high grade material is in high demand and short supply and thus often high priced and the supply unsteady. The other option, improving the material through the manufacturing process, should secure a steady, plan able supply and a better possibility to forecast prices for the material. As materials, especially high grade and high value ones became increasingly rare and die exporting countries of specific raw materials start to implement more and more restrictions, the second option seems to have high chance to grow in importance in the near future.

To exploit materials property potentials through the process, a solid understanding of mechanisms of manufacturing process have to be available for the stakeholders. The manufacturing process will become more complex which will trigger the need for a better understanding of the process, material and product and therefore information and knowledge involved to achieve the planed and customer demanded quality. To help the manufacturer to gain and handle the required knowledge and information about their manufacturing processes, materials and products, the product state based view can provide a holistic concept to compile valid information during manufacturing, including the mapping of interdependencies over the whole manufacturing process chain and identification and delivery of the relevant information to the right addressee. The concept is based on the understanding, that a product can be described by its state over the whole lifecycle by a set of relevant state characteristics. The challenge is to identify the right set of relevant state characteristics for the individual product, process and material. With this works, the authors plan to contribute to the goal of exploiting material property potential to a higher extend and reduce over engineering and thus waste of valuable resources.

Keywords*- *Product State; Manufacturing; Material Properties; Information; Process; Quality; Raw Materials

I. INTRODUCTION

The German economy evolved in an engine of growth within the European Union [1]. A large part of this success is built on the strong industrial basis, especially the showcase sector of mechanical engineering. German engineering products are exported worldwide and have the reputation of advanced technology and premium quality [2]. This reputation as high quality products is a key factor of success in the fierce global competition [3] [4]. The backbone of the German engineering success relies heavily on specialized Small and Medium Sized Enterprises (SMEs). However, being successful does not necessarily mean that there is no potential for further improvements [5]. At the same time, companies are constantly challenged to improve in order to meet the steadily increasing customer's requirements towards the quality of products and services [6].

This stand especially true for manufacturing companies [7]. Many companies focus on their core competencies and work together in collaborations and production networks to satisfy the increasing customer requirements and gain sustained competitive advantage [8] [9] [10]. All these developments lead to an increasing complexity that companies must deal with in order to remain competitive. Taking into consideration that business success of every company is based on the quality of its business processes [11], it can be said that business success of a collaborative network is based on the quality of business processes of every collaboration partner. Looking at industrial companies, manufacturing processes play an important role through the direct value adding to products.

The purpose of every process step during the manufacturing process is to add value to the product and therefore, at least in the manufacturing industry, change the products state [12] (see section IV [13] for definition of product state). In the end, the quality of a product is directly influenced by the quality of the manufacturing processes [14] [15]. Finally, the product state has to meet the customers' requirements in terms of product quality. But nowadays, this is not the customer requirement the companies have to meet, increasingly; the customer wants to have information about the product over the different stages of the manufacturing process (see Fig. 1).

In Fig. 1 an example of a distributed manufacturing process of a product is illustrated. Ideally, the product increases its value in each process step and the next process gets the product (input) with the expected parameters (internal customer).

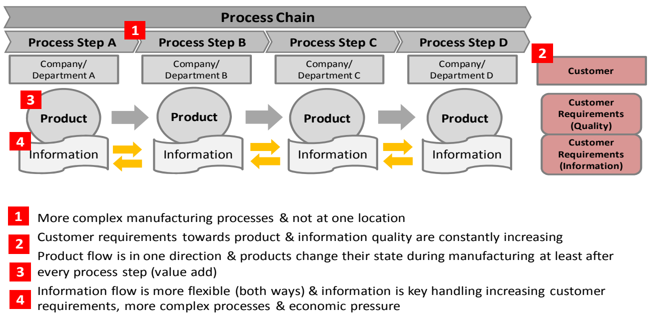

Fig. 1 Connection of Product, Process and Information towards the Goal of Meeting Customer Requirements

Practically, the process can never reproduce a process step (output) 100 % due to different factors like: external influence (e.g. temperature, Mondays); process variations (e.g. lubricant, tools); input deviations (e.g. different supplier of steel: even so the steel delivered has the same ISO No., it can vary due to the tolerance level within the norm) etc. Therefore, it is necessary to also exchange information about the product, the individual product, as well. In this case, this means not just between stakeholders with a direct interface but over the whole manufacturing process as not each piece of information is needed at every step.

Additionally, the customers increasingly insist on transparent manufacturing processes and demand comprehensive information about a purchased product. This even includes sometimes parameter settings of the machines used and source of raw materials (e.g. iron ore).

II. Material Property Potential

The trend of today's products becoming more and more optimized leads to a consistent exploitation of all achievable material properties. Especially in the steel industry this trend can be observed [16] [17]. Considering the limited availability of resources [18], limited not only by their global presence but also political regulations [19] [20] [21], and the increasing demand e.g. by emerging economies, like the BRIC countries [22] [23] [18], the aspect of efficient use of these resources grows in importance.

If processes can be optimized in a way to, on the one hand, reduce scrap and rework and, on the other hand, achieve to exploit all possible material properties as said before, the waste of valuable resources can be reduced. For example, if through an optimized process, e.g. final heat treatment, it is made possible to build a certain product from a widely available resource, e.g. steel, instead of a relatively rare resource, like e.g. titanium alloys, the rare resource of titanium will be preserved and can be put to use where it is absolutely necessary.

This observation is based on an optimization project with a first tier automotive supplier. The company was a German SME, specialized in complex products mostly impellers as part of turbo chargers for cars and trucks. The product has to fulfil a set of challenging quality requirements set by the customers, mostly automotive OEMs. The requirement highlighted in the following example, hardness, is not necessarily the most important one. It was chosen as it is a vivid example for proposed idea. The products are produced from a roughly forged object and then manufactured by different process steps like machining to the final form. In the moment, the company does not intentionally change the material properties during the process. To reach the high quality requirements, the material used is of very high quality. One example of such material is titanium alloy. With this choice of high grade material, the company ensures that the requirements are not just met but exceeded. In cases it has been found, that when an engine, equipped with such a product reached the end of life, the product itself was like new and did hardly show any abrasion. The product is generally speaking over engineered for the purpose it is planed and manufactured for, mainly due to the high grade material of choice and not like in other cases due to over dimensioning. It is possible, in this case, to manufacture the part from a lower grade material, e.g. steel, reaching the customer requirements through adjustments in the process, e.g. by adding final heat treatment. In this special case, among other factors based on the very complex geometry, final heat treatment of manufactured parts can lead to distortion problems. So if such a substitution of material is intended, the complexity of the manufacturing process will most likely increase.

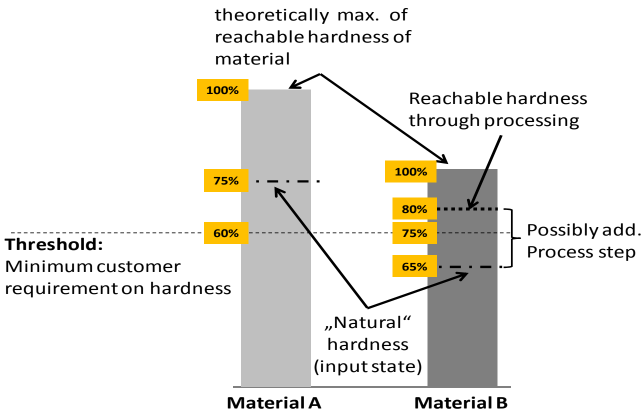

Fig. 2 Influence of Manufacturing Process on Reachable Hardness

Fig. 2 compares two materials with different properties. Material A is a very high grade material, with very good basic properties in regard to the specific requirements. The global availability is relatively low and the price is therefore high and fluctuates. Material B on the other hand, is a standard material, widely available and steady supply can be assumed. It is significantly cheaper than Material B but does not fulfil the requirements in the same way.

Given that a potential customer asks for certain specifications of the product which are translated into requirements. In this example it is the *hardness* of the final product. The threshold represents this requested hardness, e.g. 50 HRC. Material A exceeds this *threshold* without any processing as a basic material property whereas *material B*'s hardness (basic material property) is under the *threshold.* Through additional processing and adjustments within the manufacturing process, *material B* can exceed the *threshold* and meet the requirements by exploiting the material property potential. The exploitation of material property potential, extending the basic material properties can be utilized through the manufacturing process. This is a simplified example as heat treatment processes to increase hardness require careful planning and can be the source of other problems during manufacturing as the different steps of the process are interconnected and the whole system has to be taken into account [24].

For the company that can be beneficial for aspects of resource availability (e.g. wide range of suppliers) and it can even have an impact on society in terms of independence from external pressure of suppliers of seldom resources or, if the rare resource can just be retrieved with high ecological costs (e.g. extraction in open pit mines or high energy consumption).

To do so, it has to be confirmed that these desired material properties can be achieved through the manufacturing process [25]. Fig. 3 expands the perspective presented in Fig. 2 by economical and strategic factors. Again the requirements are set by customers, the market or other stakeholders and these requirements have to be met by the product. To reach these requirements, the two exemplary possibilities: taking a very good material (*Material A*) and a traditional process and taking an average material (*Material B*) and improve the properties through processing. Economically, it is important to take the price of the material (simplified: *Material A* > *Material B*) and the processing cost (simplified: *Process A* < *Process B*) into

account for an informed decision. Strategically, the availability of the materials and robust supply, now and in the future have to be considered. In this case, the simplified example just takes into account the availability on a global scale, but through restrictions or trade barriers, this has to be considered individually for every country or even every company in demand. In the next section, these aspects of raw material markets will be elaborated on in more detail. Even if these factors are not an issue today, when there are indicators that it will change in the future, companies might explore alternatives to maintain their competitive advantage.

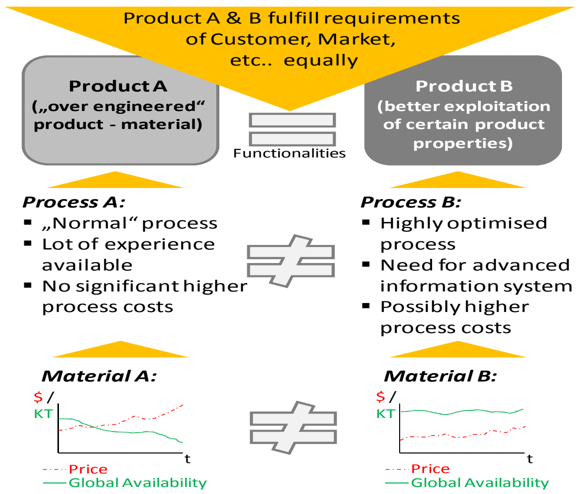

Fig. 3 Connection of Achievable Material Properties, Manufacturing Process and Usage of Natural Raw Materials

Therefore, a detailed understanding of the manufacturing processes and their influence on products and in the end, their product state, becomes progressively more important. Continuous improvement of the industrial manufacturing processes can be a way to stay ahead of competition. It is necessary to take a closer look at what impact the increased overall complexity in the global business environment of mechanical engineering companies has on collaborative manufacturing processes. One important factor is the rapidly increasing need for information exchange between companies/business units with all the pitfalls, which among other things include: communication problems, security issues, interface problems of IT systems and, of course, the sheer amount of information to process.

In order to connect the aforementioned achievement of exploitable material properties and the developments on the global raw material market, the next section will summarize these developments and introduce a pricing model for raw materials.

III. Natural Raw Materials Markets

In general, there are different definitions of raw materials. Within this paper, raw materials are understood as commodities and goods that possess an inner value and product appeal. This inner value or product appeal is based on the usage in industrial manufacturing and the demand of specific customers [26] [20]. Raw materials can be very diverse. They reach from commodities like oil, gold, platinum and coal to agricultural products like corn or lean hogs. Raw materials are not unique in character. Other than for example art pieces or houses, raw materials can be replaced without problem [27]. The usage and inner value alone defines raw materials as the good highly demanded as it is today.

Raw materials in general exist in a limited quantity. There are raw materials, which are rather rare (quantitatively) on a global scale like e.g. gold or widely available e.g. like coal or oil. At the same time the global allocation of the raw material deposits is not equal. On the one hand side, there are regions in which economically usable raw materials are common and on the other hand, there are regions which possess just very few economically usable raw material deposits. That has to be understood, that the availability of certain raw materials plays a crucial role for the economic strength of a society [19].

Supply markets of raw materials partly distinguish themselves strongly from other supply markets, e.g. industrial or consumer goods. One specific characteristic or raw material markets is the global perspective. Whereas the consumers of raw materials are often located in Europe (EU), North America (NAFTA) or Asia, a lot of the raw material deposits are located in regions which have a less developed industrial infrastructure. Therefore, there is a strong global competition and raw materials are dealt globally for one price and, furthermore, are partly subject to speculative transactions [28].

In Fig. 4 the influence of selected key variables on raw material prices, as well as the inter-dependencies of different influencing factors are presented. A central aspect of Fig. 4 is the, especially with raw materials, importance of supply and demand [18] [19]. It is common, that the supply is radically run short if the return on investment is too low. Not until the market price for raw material is getting better, production and therefore the supply is ramped up again. In case of a surplus supply, the result is accordingly falling market prices [28].

At the same time, the big influence of available capital shows: it directly influences the available supply and simultaneously, indirectly through industry structure and industrial production, the demand. The technical advances are very important as well, also directly influencing the supply and indirectly the demand not only through industry structure and industrial production again, but also through recycling of scrap material the demand [18]. The available geological resources are of course a very basic indicator. But the availability is directly influenced of the price level, as with a high or rising price the deployment of otherwise unprofitable deposits begins to make economic sense and the global availability increases. The same logic is behind the substitution processes and more efficient utilization. These points are directly connected to the manufacturing process improvements in the previous section. Both variables are directly influenced by the price for raw materials and influence the demand themselves.

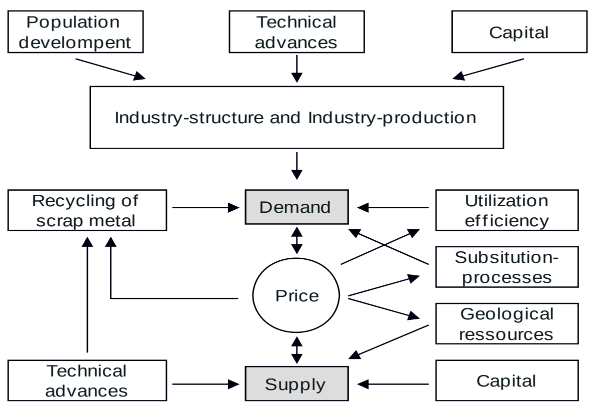

Fig. 4 Key Variables in the Development of Supply and Demand in Raw Material Markets [19]

The key variables presented in Fig. 4 are not the only ones. In general, there can be observed interdependencies between the crude oil price and the pricing of raw materials. This can be traced back the the high impact of transport and extraction costs on the final price. This interdependency can lead to considerable and hardly predictable price variations.

The geopolitical location of many deposits is often in politically unstable regions of the world [29]. Therefore, the raw material price can also be strongly influenced by political events, both regionally and globally [19]. Additional to this, currency fluctuations add to the price variations if the customer and producer are located in a country where the US$ is not the currency [55].

A tendency in the raw materials industry is also, that through the size of the operation, and therefore more efficient usage of deposits and (expensive) equipment, high Economies-of-Scale (EoS) can be achieved. Additionally is the exploration and extraction of raw material deposits very capital intensive and needs high investments which can mostly just be provided by Multinational Enterprises (MNEs) with the adequate financial power. These points lead to a general tendency towards consolidation within the mining and extraction companies. The resulting MNEs represent, based on their pure size and controlled deposits a certain market power [19].

Within raw material markets it can be said, that one always has to be aware of relatively sudden price changes, especially for raw materials with few deposits or just few supplying companies/countries. Therefore, the market should be monitored constantly and precautionary measures towards a sustainable supply should be considered by every manufacturing company depending on such raw materials. One of those precautionary measures could be to look at the own manufacturing processes and opportunities to liberate oneself to a certain degree from fluctuating and unsteady supply conditions through intelligent process improvements. In the next section a concept for a new view on information management in manufacturing will be presented as one possible way in this direction.

IV. PRODUCT STATE BASED VIEW IN MANUFACTURING

The very complex industrial manufacturing processes consist of various manufacturing process steps (see Fig. 1), each adding value to the product. Adding value to the product can be done in various ways, e.g. by changing the physical form, hardness or extending the usability by adding services. Each process step depends on information pertaining to the input state of a product. There are two ways how this can be achieved.

On the one side, the information can be provided from the design of the product. In this case, the information used is based on the state that it is expected to be. In this variation no deviation will be taken into account, as the possibility is not included in the system. A variation of this way is to have a quality control of the input state so products passing the test will be allowed to go through the process step. The downside is, this is expensive (through e.g. extra staff, scrap material depending on the percentage of passing products, measurement technology etc.) and time-consuming.

On the other side, the input information can be generated based on the individual product state at the time of the beginning of the process step. The information here is more likely to be accurate as it takes the variations that can influence the process quality into account. In order to provide each step with the individually necessary information, it is essential to be able to describe a product.

This can be done in various ways. Most likely the manner of describing an industrial product, e.g. gear made of steel, will be different from the description-style of a design product, e.g. a plastic rear mirror. At the same time, the individual describing a product influences the description based on, among other things, his or her own background, knowledge and experience. Therefore, the approach of describing a product through its product state (see Fig. 5) [13] will help to align the descriptions in a commonly understood manner as well as increase transferability and usability of accompanying information by the addressees.

The product state itself is defined as follows: “The product state describes a product at a certain time during the production process or after through a combination of state characteristics. State characteristics are definable and ascertainable measures, which can be described in a quantitative or qualitative way, e.g. weight or chemical composition of the material. The product state changes due to external influence, for example machining or corrosion from t=0 to t=1 when at least one descriptive state characteristic changes” [13].

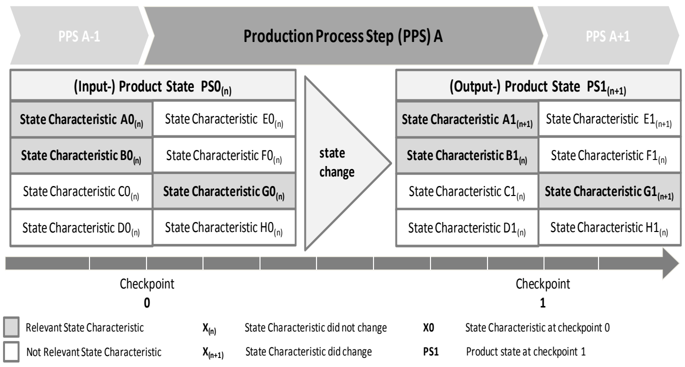

Fig. 5 Describing a Product by its State Using State Characteristics [30]

In this paper, the term product is used comprehensively to describe an artefact over various stages of its product-life-cycle replacing the more technically accurate terms e.g. component or work-piece during manufacturing. The consistent use of this term reduces complexity by emphasizing that the focus lies on one individual product over different stages of the product-life-cycle.

V. INFORMATION IN MANUFACTURING PROCESSES

Within this section, first the importance of information management in modern manufacturing processes will be elaborated on. Secondly, product state based information is introduced and finally possible usage of product state based information to improve manufacturing processes in order to achieve the desired product properties will be presented.

A. *Information Management in Manufacturing*

Along an industrial manufacturing process chain, physical products as well as information are exchanged between the partners [31] (see Fig. 1). The availability of information is a precondition to adjust each production process step in such a way that the outcome reflects the set quality requirements to a high degree. Quality, as stated before, constantly gains importance for the customer and for a sustainable use of

resources. At the same time, distributed production brings forth new challenges for managing quality [32].

First, a clear understanding of information is needed in order to develop the proposed idea further. Even so, Fig. 6 below indicates that the different terms (e.g. information and knowledge) can be clearly distinguished; this is not the case as solid measures are missing and there is a large gray zone in between the different terms.

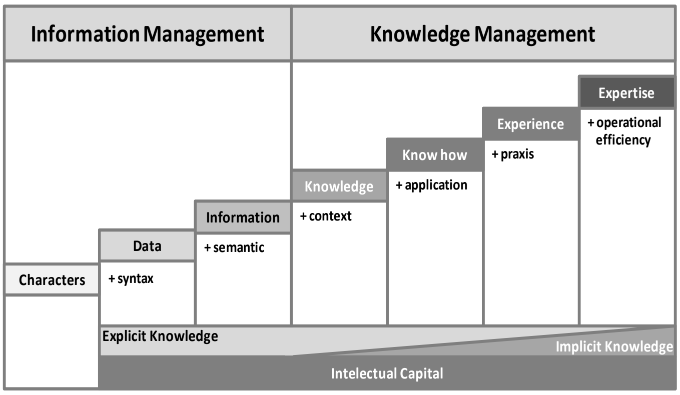

Fig. 6 Differentiation of Knowledge, Information and Data Management [33] [34]

Knowledge Management (KM) is the systematic and explicit control of knowledge based activities, programs and governance within the enterprise with the goal to make effective and profitable use of the intellectual capital [35]. [36] emphasize that knowledge management does not only imply successful utilization of knowledge but also creation and allocation. The KM research field is a very broad one and there are various research areas involved, from social science over psychology and business to engineering. Therefore, the number of publications and available information is vast. Setting the focus on identifying knowledge, [37] with their model of knowledge building blocks defined one of them as “knowledge identification” [37]. Taking a closer look, this block describes the need to increase transparency of internal and external sources of knowledge. It also is supposed to ease the way the own employees have access to knowledge needed. The pioneers in the field of knowledge management, [38] created the well-known model of the “knowledge spiral”, an illustration of the knowledge creating process focusing on transforming implicit to explicit knowledge. Other concepts, like e.g. process oriented knowledge management [39], are variations or combine the models of Probst et al. or Nonaka & Tekeuchi and combine it with other theories like Porter’s value chain [40]. None of these approaches and models offers a defined and accepted concept to clearly identify very specific sources of information or data about an individual product or process. But they all emphasize the importance of having the right knowledge or information available at the right place for all business processes. Research of the strongly related Information Management (IM) in manufacturing is mostly focused on how already existing information has to be managed (e.g. [41] [42] or what existing IM system should be chosen (e.g. [43] [44]. The general principles of IM (e.g. [45] [46] [47], the right information at the right time in the right granularity at the right place in the right quality can be seen as the general vision this research builds on without providing a problem definition for the domain or a proposed solution.

B. Product State Based Information

One lever to improve manufacturing processes is to look at the data and information involved and how this information is put to use [42]. As stated by [48], the successful coordination of a manufacturing process is mostly based on a successful handling of information to support process management and other tasks involved. With today’s advanced ICT it becomes possible to process, transfer and store large amounts of data and information for a reasonable price [49]. But too much information can be a threat for improved process quality. [50] emphasize the importance of the availability of the right information for quality during manufacturing processes. Hence the question is: What is the right and relevant information in the case of distributed manufacturing process chains and high tech industrial products to achieve the material properties?

Information exchange is executed over interfaces. These interfaces can be within one company, but interfaces overlapping company borders are an even bigger challenge, given problems like different ICT infrastructure, organizations and so forth [51]. The question of what is the right and relevant information gains in importance within a collaborative production environment. In such a constellation not only different persons or IT systems can complicate matters, but also different corporate cultures or guidelines. In general, in an age of supply chain competition the stakeholders have a general interest in reaching the best performance of the whole supply chain [52].

In manufacturing companies, many process steps operate automated. Every process step needs information about the product at the beginning of treatment to adjust the machine parameters. In an automated process chain, the information of the product is often not individual for the specific product at a specific time but derived of planning and design. To assure an optimized handling of the individual product at a specific process step during the manufacturing process, information of the current product state (input product state) is necessary. The more precise and the more complete the information relevant for adjusting the process parameters is available, the better the machines can be adjusted and the more the quality of the product will be enhanced.

This paper at the current state is focused on engineering SMEs with no classic mass production but single item or small charges production of individual highly stressed products. This does not however mean the concept cannot be extended or adjusted to other organizations with different product portfolios. The reasons for the current focus on this group are that these individual specialized products mostly use expensive materials, and the manufacturing process is very complex and costly. Hence, the circumstances within manufacturing processes of this group address the main statements of the theoretical product state concept from the beginning to a large extend. These players will most likely be among the first who are forced to think of new methods and concepts to address the issues coming with increased need for resource efficiency and quality. Furthermore, the customers expect premium quality and rework or scrap parts have a big impact on the companies’ profits [24].

In the following Fig. 7, the process owner gets all the relevant information about the current state of the product at the right time to adjust the parameters of the process step

accordingly. To be able to do that, it has to be known what information is relevant for the whole manufacturing process and the individual process step. The set of relevant information for the whole manufacturing process will not change over time as it contains all necessary information for each step. The set of relevant information for each manufacturing process step on the other hand is individual for each process step based on the information needs. In practice, as still many interdependencies and phenomenon's are not yet discovered, this set of information for the user in need is not a given.

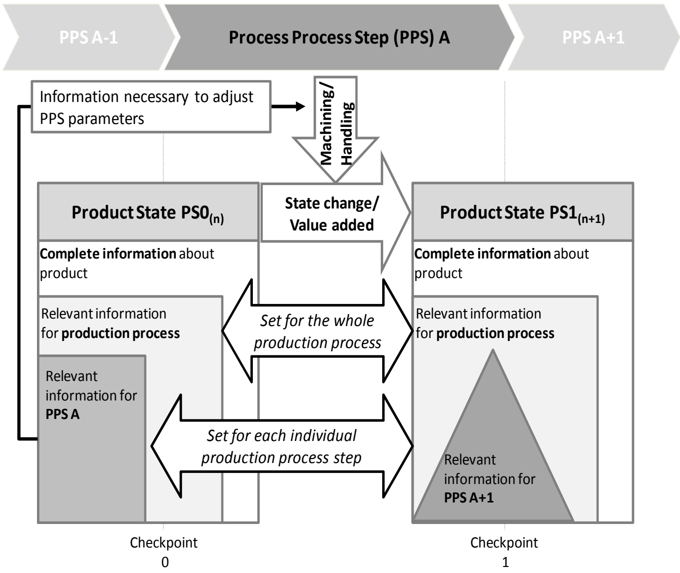

Fig. 7 Information/Data Clustering of Product State Based View

Concluding, companies today have to deal with a business environment of increasing customer requirements towards product and information quality and harsh global competition. The product and information quality strongly depend on the process quality, especially in manufacturing of high-tech products where the whole process chain including interdependencies has to be taken into account concerning quality deviations (deviations from planed customer requirements).

C. Using Product State Based Information

In Fig. 8, a process step is illustrated based on an input/output-model (compare [53]) and extended step by step by adding further information from a) to d). The top left, part a) of Fig. 8, shows the basic input/output-model of a process step creating value through transformation of input to output. Transformation in this case describes the change of the product state, and thus of one to n relevant state characteristics, from input (product state) to output (product state). Every process step has an input product state which deviates to a certain extend from the originally planned input (see Fig. 8 b)) [54]. These deviations of the input product state have an influence on the output product state after the state change (transformation) during the process (see Fig. 8 c)) [50]. By adjusting the process parameters for the transformation during the process, the output deviations can be reduced and therefore either the input deviation of the following process and/or the final product itself (see Fig. 8 d)). To be able to adjust these process parameters accordingly, questions like "On what basis are the process parameters set?", "What information is used to adjust these?" and "How can the 'right' information be derived?" have to be taken into account.

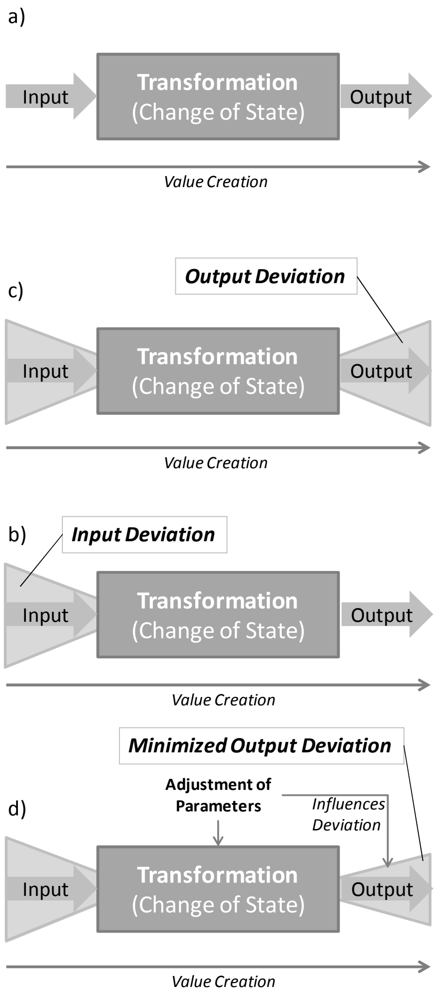

Fig. 8 Quality Deviation Based on Process Parameters (see [53])

One option is to base the adjustment of the process parameters on information of the product, for example the input product state. Taking interdependencies and the process view into account, this information can be provided through a modelling of the product state along the distributed manufacturing process chain. The comprehensive approach can contain all necessary information needed by processes involved.

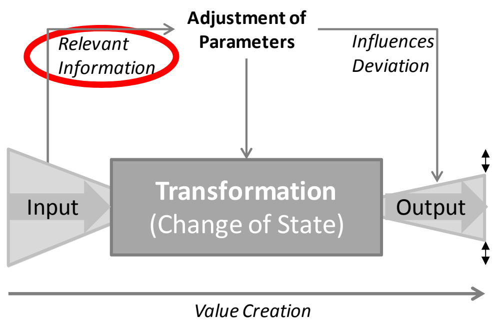

Fig. 9 Possible Application Area of Indentified Information

Yet today, there is no model or approach on how to derive a set of relevant product state characteristics for distributed manufacturing process chains to provide the needed information for process parameter adjustment (see Fig. 9). With such a set, the information basis for an effective

adjustment of process parameters and thus a smaller quality deviation as a process output can be achieved. A special focus within such a concept has to be laid on the question, how can the relevant information which provides the basis for the adjustment be identified. And there lies the challenge which a product state based view concept tries to tackle trough transparency and decent understanding of the interdependencies, mapping (tracking and tracing) and distribution of product state characteristics.

VI. CONCLUSIONS

In this paper, first, today's challenges for manufacturing companies, being stuck between global competition, increasing customer demands towards quality and raising raw material prices were elaborated on. Second, the possibility of exploiting the material property potential through manufacturing process improvements and thus substituting rare raw materials through ones more widely available was presented. In the next section, the special characteristics of the raw material market including the influences on pricing were summarized. In the following, the product state and the product state based concept as a holistic view on information and quality management in industrial manufacturing processes were introduced. This section was directly followed by elaborating on information in manufacturing processes, again based on the introduced product state concept. Within this section possible ways of how product state based data can be exploited within the process to enhance the process quality and thus the final product quality.

In a world with ever increasing population and industrial production, and thus, increased demand for raw materials combined with physically limited supply, new ideas for manufacturers how to handle this complex situation are needed. As raw material resources are limited, one possible way is to focus on improvements of manufacturing processes in a way to reduce the usage of high grade / high value raw materials were it is not absolutely necessary. Through new research findings and the possibilities of modern technology especially in the information technology sector, it is possible today to gather and utilize individual product information more efficiently also on a large scale. The goal of exploiting the achievable material properties to a high extend in order to "upgrade" lower grade raw material for high end products that meet the customer requirements can be achieved through managing manufacturing process and product information for the whole process chain. Through our work around the introduced product state based concept, the authors plan to contribute to the goal of exploiting material property potential to a higher extend and reduce over engineering and thus waste of valuable resources. To do so, the product state based concept combines not only a very detailed view on the product and material itself, it incorporates also the process perspective and, which is very important, the system view including process step overarching interdependencies.

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